A Strategy for more uniform assessment of soil disturbance

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Abstract

More uniformity is needed in describing, monitoring, and reporting soil disturbance from forest practices and research. We review the need for: (1) more uniform terms for describing soil disturbance; (2) cost-effective techniques for monitoring or assessing soil disturbance; and (3) reliable methods to rate soils for risk of compaction, rutting, topsoil displacement, and perhaps erosion. A number of products are listed to facilitate collection of more comparable data by states, provinces, USFS regions, and private ownerships, and also ensure a more seamless process for reporting at national and international levels where appropriate. Additionally, these products will improve operational relevance of research results.

Keywords: soil compaction, soil displacement, soil erosion, sustainability protocols, Montreal Process, monitoring, risk ratings for soils

Introduction

Physical disturbance from some forest practices can affect soil physical, chemical, and biological properties. Soil disturbances of concern to forest managers include compaction, puddling, rutting, organic matter and topsoil displacement, and disruption of soil drainage. Although these disturbance types occur in a continuum, it is possible to classify disturbance into generally applicable, readily identifiable, and operationally relevant categories. These disturbances may affect soil capacity for water infiltration and storage, tree growth, or soil erosion. Consequences depend on the severity and extent of disturbance, and on the soil and climate where disturbance occurs.

Comparisons of results from research and operational monitoring, and comparisons of guidelines and standards have been hampered by a lack of common language and the resulting proliferation of protocols for assessing soil disturbance. Moreover, reporting of monitoring data within individual organizations, across different jurisdictions, and to third-party certifiers has often been inconsistent and ineffective. To achieve common language and monitoring protocols, however, requires integration of considerable information.

Our objective is to provide and discuss a strategy to deal with all types of soil disturbance, especially those caused by harvesting and with potentially detrimental consequences to site productivity or hydrologic functions. In our discussion, we do not impose value judgements about disturbance types, nor do we prescribe adherence to specific measurement protocols or risk-rating systems. We do advocate more uniform language and approaches. Our role as scientists is to provide technical direction that enables effective communication and comparison of operational and research results. We provide a problem statement with background information and our recommendations for each of the following elements: (1) more uniform terms for describing soil disturbance; (2) cost-effective techniques for monitoring or assessing soil disturbance; and (3) reliable methods to rate soils for risk of compaction, rutting, topsoil displacement, and perhaps erosion. These problem statements and recommendations are intended for forest operations, policy, and forest soils research across all regions. Background information largely draws upon experience and examples in British Columbia and the Northwestern U.S.A, referred to herein as the Pacific Northwest.

Develop more uniform categories and definitions of soil disturbance.

The objective is to have clear, unambiguous definitions of disturbance that enable precise, consistent, and cost-effective monitoring, as well as assessment and communication of operational and research results.

Problem statement

Classification systems exist for characterizing soil disturbance. Some define severity classes of soil displacement, mixing, rutting, and compaction. Others define and count (record) some disturbance types only when these are of specified area or width, thus assumed to be detrimental to site productivity or hydrologic functions. Consequently, it is difficult to compare guidelines, standards, or operational and research results without first correlating the different systems and developing a common language for such comparisons. Criteria are needed for more uniform descriptions of visually observable compaction, puddling, rutting, and scalping (displacement).

Background

Soil disturbance results from construction of access roads, harvesting and site preparation that leaves various patterns of disturbance from machine actions and transported logs or trees. With intensive utilization, some sites have disturbed soil on nearly 100 percent of their area (Robert Campbell, Weyerhaeuser Co. personal communication).

Dispersed (in-block) disturbance

Soil disturbance is regulated based on changes in soil properties and/or visually identifiable categories of concern. These systems are based on research results and

interagency field evaluations. An example visual system is in B.C., where allowable area of disturbance and the threshold severity at which disturbance is counted at each site is based on hazard ratings for compaction, displacement, or erosion. Counted disturbance is considered potentially detrimental to tree growth or site hydrology. To prevent anticipated cumulative effects, allowable area for dispersed, counted disturbance is limited by most jurisdictions. For example, in B.C. this currently ranges from 5 % of the harvested area on sensitive sites (e.g., sites with a very high disturbance hazard) to 10 % on less sensitive sites.

In jurisdictions where critical threshold levels for various soil properties are set, these have not been widely assessed or validated. Criteria for compaction focus on absolute or relative changes in bulk density, porosity or soil strength, all of which are time-consuming and difficult to measure on a routine basis.

The Pacific Northwest Region (USFS) is currently aligning their assessment methodology with the visual disturbance-class approach used by Weyerhaeuser Company (Fig. 1). On the Wallowa-Whitman National Forest, a four-class system is being tested (Table 1). Although the Region has worked with the PNW Research Station to test consistency and repeatability of disturbance observations, no final version of qualitative definitions of soil disturbance or of recommended assessment protocols has been specified. The B.C. disturbance types are included in Figure 2 and Table 2.

Internationally, ruts appear to be the most common disturbance type recognized by various agencies and researchers.

Access roads

Some provisional definitions follow:

- Permanent access includes roads and landings, and any harvesting or yarding trails that will be used repeatedly in partial-cut systems. Permanent access typically is considered a permanent loss from the productive forest landbase and often requires tracking under international sustainability-protocols and third-party certification. To compare area occupied by roads, we need common protocols for width measurement.
- Permanent trails that are excavated and bladed also require similar protocols for width measurement.
- Temporary access includes roads, landings, or trails that are not needed until the next rotation. Some temporary access will be rehabilitated to restore productivity and/or hydrologic functions, but other trails are not rehabilitated, either because of no requirement, very short length, or because they represent less concern for site impacts (e.g., winter trails).
- Rehabilitated roads are increasingly an operational objective to reduce maintenance and risk of stream sedimentation. Criteria should be established to judge completed (successful) mitigation.

Why improve uniformity of terms?

Improved communication within individual agencies with forest workers, and with local and international customers may be the most important reason for developing common language for sharing information about soil disturbance. Poor or incomplete understanding of soil disturbance categories can lead to inconsistent application of standards and reduced public awareness. Rather than being caused by insufficient training, problems like this are more likely caused by current definitions of soil disturbance that are not based on visually discernible, qualitative criteria, but that instead require quantitative sampling and lab analysis. Moreover, soil specialists may thoroughly

assess soil conditions within proposed activity areas before prescribing soil management objectives, but application of this information is ineffective when contract administrators and operators lack understanding and ability to identify disturbance categories. Consequently, undesirable soil conditions often result from misunderstandings or miscommunication.

Government agencies also must deal with many disparate groups having different perceptions about soil disturbance and its effects on productivity and ecosystem functions. Based on their interpretation of soil quality standards, any of these groups can stop or delay particular projects through legal action. The likelihood of dealing with these adversarial situations more effectively will increase if all participants use the same terms and definitions. Improved communication is extremely important to those committed to maintaining or enhancing forest soil productivity.

Uniform language and procedures for describing, monitoring, and reporting disturbances would also assist communication across jurisdictions. Efficiency of soil disturbance assessments could be improved further by sharing in development of training materials, brochures, and monitoring protocols.

What disturbance is detrimental?

Most soil scientists and foresters recognize that not all soil disturbance is detrimental. One general definition of soil disturbance is "any disturbance that changes the physical, chemical, or biological properties of the soil" (Lewis et al. 1991). Note that the direction or consequences of these changes are not specified. Foresters, for example, commonly prescribe soil disturbance as site preparation for seedling planting and establishment. Disturbance related to these activities is usually not considered detrimental or counted as disturbance by various jurisdictions' soil-disturbance guidelines.

Some basis is needed for deciding when a given disturbance type or severity is counted or considered detrimental. Regional studies should be used to determine which types of disturbance actually affect tree growth or hydrologic functions. The actual effect of a given disturbance category and severity on tree growth at a given site will depend on factors that are growth limiting and how they change over a rotation. For example, common growth limiting factors in the B. C. Interior include: soil moisture (drought or excess), extremes of soil temperature, summer frost, limited rooting volume, soil nutrition (e.g., calcareous soils), competing vegetation, and root rot. The consequence of disturbance for tree growth is the net effect of soil disturbance on the original and the new limiting-factors. For example, compaction initially can reduce soil aeration, but concurrently reduce competition from vegetation. Long-term effects depend largely on how these interacting effects change over time

Some types of soil disturbance can be ameliorated, others cannot. Rehabilitation of detrimental soil disturbance should be recognized as a desirable strategy when soil conditions are suitable (Terry and Campbell 1981; Curran 1999). Tillage cannot always be used to ameliorate compaction and improve soil conditions for growth. Other treatment options may be appropriate.

Regardless of their effects on tree growth, some types of soil disturbance are of concern because of their potential consequences for on-site hydrology and associated downslope (off-site) impacts. In some jurisdictions, the primary reason for soil disturbance guidelines is to protect water quality and fish. Although erosion and sedimentation are readily visible, other hydrologic changes are more difficult to discern. Therefore, an informed risk-management approach is adopted, which is based on best-available information (Anonymous 1997). Hydrologic effects may also influence tree growth by altering drainage or by exporting water normally available to trees during dry

weather. Because summer drought is generally one of the most growth-limiting factors in the Pacific Northwest, these on-site hydrologic effects may impact productivity on an entire harvested area and also may confound comparisons of tree growth on apparently undisturbed versus disturbed microsites (Kuennen et al. 1979).

Ultimately, thresholds for unacceptable disturbance should be based on actual, confirmed effects on tree growth, site hydrology, and other resource values. In the absence of demonstrated such relationships, there is a tendency to err on the conservative side because it is generally easier to prevent widely dispersed detrimental disturbance than to repair it.

Recommendations: Review existing soil disturbance classifications. Decide on common themes and simple categories that are operationally relevant and convenient for reporting results.

Develop unanimous definitions to facilitate meaningful comparisons and learning from soil-disturbance monitoring. Suggested requirements for a common language include:

- Categories cover the range of soil disturbance likely to occur with forest practices.
- Disturbance categories are visually discernible, readily recognized by equipment operators in the field, and linked to quantitative data.
- Disturbance category definitions can be understood and easily recognized by laypersons.
- Disturbance types are strongly correlated to more quantitative measures or thresholds for judging detrimental disturbance.
- Distinctions are made between soil types in determining those disturbance categories counted and those that are not.

- Consistent definitions are provided for both permanent and temporary access, and for rehabilitated disturbance.
- Definitions are consistent with a strategic database documenting types and severity of disturbance and effects on site productivity or hydrology. Quantifying (researching) the practical consequences is the most important step of any process for protecting or enhancing soil productive capacity.
- Technical committees currently operating or proposed for regional, national, and international levels should compare soil management procedures and tools, and should explore opportunities for improving consistency among approaches

A first step might be to evaluate several existing disturbance classifications for use as soil quality indices. Specifically, one might examine how each classification scheme relates to changes in key soil functions (e.g., nutrition, gas exchange, soil strength, water-holding capacity, infiltration). A second step could be to determine how the scheme will vary with local soil properties to reflect how these relate to specific soil functions that locally limit productivity or hydrologic functions. It appears that none of the current categories or thresholds can consistently index soil changes that are biologically relevant. Although consistent or uniform indexing may not be achievable, categories or thresholds should represent a justifiable mix of quantitative evidence and assumed or a priori relationships between soil factors and tree or hydrologic response.

Concurrently, disturbance categories and guidelines specifying thresholds for severity and extent should be revised as results become available from monitoring, operational trials, and research studies like the Long-Term Soil Productivity (LTSP) network (Powers 200x). Disturbance category definitions and thresholds should be consistent with BMPs for maintaining soil productivity and hydrologic integrity.

Soil restoration practices must be evaluated to determine their effects on productivity and hydrologic function. Criteria are also required for defining soil rehabilitation objectives and for determining when rehabilitated soils are no longer counted as disturbed.

Develop cost-effective monitoring techniques that facilitate reliable comparisons of operational and research results among regions.

The purpose of monitoring soil disturbance is to estimate the percentage of a total area in specified disturbance categories. Sampling methods should provide representative coverage of an activity area (or of a representative sub-area), and allow for statistically valid and cost-efficient estimates.

Problem statement

Numerous methods exist for surveying or sampling soil disturbance in operational units and research trials. Although some methods have been developed, tested, and selected based on statistical principles, their precision, accuracy, and cost should be documented and evaluated.

We need cost-effective approaches for operational assessments or monitoring that also provide statistically valid and scientifically relevant data. Many agencies or groups have already developed and implemented soil-condition assessments. The Pacific Northwest Region of the USFS developed such procedures (Howes et al. 1983), but soon learned that their implementation was expensive and often cost-prohibitive. As budgets declined, the amount of monitoring dropped to almost nil; this situation drives efforts to develop more cost-effective protocols. Our intent is to promote valid documentation and evidence of good stewardship of the soil resource, at reasonable costs.

Background

Sampling designs

In developing early guidelines for reducing soil disturbance, a number of monitoring methods have tested, selected, and used. A number of these methods were reviewed and compared by McMahon (1995). Formal surveys range from traverse surveys of defined disturbance features (e.g., roads and landings) to sampling transects for more dispersed features (e.g., equipment trails and localized rutting). Traverse surveys either completely traverse a feature (e.g., a landing) or measure its length and sample to estimate mean width (e.g., roads, skid roads, or skid trails). Transect-sampling methods included point-sampling along transects that are randomly or systematically located (e.g., Smith and Wass 1976), and continuous-line transects used by various agencies. Random, continuous-line transects were adapted into a cluster sampling method (two-stage sampling) by the USDA Forest Service (Howes et al. 1983). Subsequent B.C. Forest Service efforts led initially to a combination of the two techniques (Curran and Thompson 1991), and later to simpler, parallel transects with data analyses based on the binomial distribution (B.C. Ministries of Forests and Environment 1995a). Parallel transects should cross the main pattern of disturbance and cover all or a representative portion of the activity area.

To avoid the expense of formal surveys, informal methods can produce rapid evaluations of active operations or at final inspection. Informal surveys often provide the basis for recommending or requiring formal surveys. Several protocols have been developed for visual walk-through estimation of disturbance; these often involve pacing or hip-chaining along transects to estimate average coverage and to ensure disturbance is

not concentrated in sensitive areas. Confidence limits are seldom appropriate for informal assessments because they imply more precision than the method would support.

Other approaches have used aerial photos or even global positioning systems mounted on harvesting equipment. Combinations of such methods might be used to assess landings, temporary roads, and skid trails.

When guidelines are based on visual criteria, both formal and informal surveys provide reasonably efficient monitoring, reporting, and enforcement of soil disturbance standards. Costs increase markedly when guidelines are based on quantitative disturbance criteria, such as percent change in bulk density or aeration porosity, which require sampling of soil physical properties. Cost associated with quantitative measures may be prohibitive. For assessing regulatory compliance, chosen method(s) must fit the intended use, and strike a balance between cost and enforceability. One way to reduce costs is to use statistics based on the binomial distribution. Moreover, considering each observation point in the survey as independent, the observer gains a larger sample size when compared to two-stage sampling used by the USFS (Howes et al. 1983) and previously by the B.C. Forest Service (Curran and Thompson, 1991). This provides narrower confidence intervals.

Total amount of soil disturbance in an activity area can be composed of many small polygons or a few large ones. Therefore, pattern and distribution of disturbance should be documented in monitoring reports. Even areas of soil disturbance can remain undetected when the survey area is large and sampling intensity low. One solution is to restrict quantitative or detailed disturbance monitoring to a smaller sub-area that is either representative or purposefully selected as worst-case disturbance. Purposely selecting a smaller area (e.g., 1 ha) for efficient survey and enforcement, however, requires agreement among contracted parties. Therefore, guidelines and contracts should state

explicitly how and why this purposeful selection will occur to ensure compliance with the standards. After selection (stratification), a survey using parallel or random transects is conducted on this smaller portion of the total area.

What is the sample?

Another monitoring consideration is defining the sampling unit (observation). For continuous-line transects, the distance intercepted by each disturbance type is recorded and its percentage of the total transect length is calculated. When simplifying this line-intercept method by using point observations, the discrete points (e.g., every 3 m on the line) are the sample. If a point falls on a counted disturbance (type and specified size), it is recorded as disturbance. This sampling method is efficient and statistically sound. A target of 500 points should be assessed along transects for the binomial distribution to yield narrow confidence intervals (B.C. Ministries of Forests and Environment 1995a). This is more efficient than other methods that collect as many as 1800 observations (e.g., cluster sampling), but yield a wider confidence interval due to reliance on the normal distribution because the individual points can not be considered independent and the number clusters being statistically summarized may equal 30.

Sampling intensity

When setting sampling intensity, one should consider the consequences of making a wrong decision (based on the sampling data). A manager may want more precise information (hence a larger sample) if: (1) a decision is to be made about contract violation or rule infraction, (2) information is to be used in court proceedings, or (3) effects of new equipment are being evaluated. In contrast, less precise information may suffice for: (1) assessing performance relative to broad standards and guidelines or (2)

evaluating investments in restoration. Managers must understand that some differences between estimated and actual values are expected, and that refining estimates may be costly. Managers must also understand that there is a point at which the marginal benefit (increased precision) realized from additional expense approaches zero.

Desired sampling errors and levels of confidence must be set before establishing sampling intensity. These will depend on the decisions being made from the data and on the risks deemed acceptable by those conducting (requiring or approving) the survey. For example, Weyerhaeuser Co.'s sampling intensity was developed from several field trials where a predetermined acceptable margin of error was set. For compliance, or enforcement monitoring, decisions are required about confidence limits about survey results from a given area. For example, if a survey data indicates that 18% of the cut-block was detrimentally disturbed, does this exceed the 15% standard? In British Columbia, the lower 90 % confidence limit is used for compliance (B.C. Ministry of Forests 2001). If the 90% confidence limits were 18 ± 5% in our example, then the standard was not exceeded. As stated by McMahon (1995, p. 32): "...where single (sic. non-replicated) surveys are being used to assess site disturbance, it is necessary to recognize the inherent variability in estimated results. This is particularly important when using the assessment results to determine compliance with a quantitative standard."

What is recorded?

Some protocols document all soil disturbances, while others record only counted or detrimental disturbance. To ensure comparability of results, documenting all disturbance categories is preferable. This allows for maximum use of the data for comparisons as well as for tracking beneficial disturbance. Moreover, counted disturbance can be derived when sensitivity to disturbance types is known or assessed.

Which disturbance is "counted" varies greatly across jurisdictions, partly in response to regional differences in soil resilience, but also is due to different evolution of guidelines. The Pacific Northwest Region (USFS) has struggled to determine what patterns of disturbance (size and shape) should be considered "detrimental" to soil productivity when conducting assessment surveys. Currently, there is a minimal or threshold size-limitation for counting soil displacement as detrimental (100 square feet and 5 feet wide (9.29 square meters and 1.52 meters wide)). Alternatively, it may be better to record actual conditions at each observation site, a point- or intercepted length, and then annotate or map how each disturbance category is distributed throughout the sampled area. Otherwise, more disturbance types should be identified to capture objects of concern under the guidelines, such as the larger scalps referred to above. Current guidelines for this USFS Region state that no more than 20 % of a site may have soil in detrimental disturbance classes, including permanent and temporary access roads (USFS, 1998). Each Region of the Forest Service has developed its own policy and standards that can be found in various locations within their directives system.

Currently in B.C. guidelines, permanent access roads and landings are limited to 7 % on a cutblock basis. In-block limits for counted soil disturbance are defined in the Forest Practices Code. Two main types of disturbance are recognized, machine tracks and displacement. The legal definitions of these disturbance types are summarized in Table 2, with diagrams in Fig. 2. Machine tracks include excavated and bladed trails (skid roads), and disturbance from overland skidding. Excavated and bladed trails (skid roads) are considered temporary access that must be rehabilitated and their area, in combination with that of dispersed disturbance (displacement), must not exceed a specified percentage of the cutblock area that will be reforested (e.g., 15 % before rehabilitation and 10 % after, on less sensitive soils). On more sensitive sites (those with High and Very High

Compaction Hazard), more disturbance types are counted (e.g. 5-cm deep ruts and impressions, as opposed to 15 cm on less sensitive soils) and the limit is lower (e.g., 10 % before rehabilitation, and 5 % after).

Inferences from disturbance monitoring

Monitoring estimates the severity and extent of soil disturbance. From this indirect evidence, an analyst can speculate about subsequent consequences for tree performance or hydrologic functions. This indirect approach is used because collecting direct evidence (measuring tree growth or hydrologic functions) is time consuming and costly. Clearly, operational monitoring must be supported by concurrent research to relate tree growth to disturbance. Such research supports local estimates of productivity declines or gains that are used to predict long-term yields, and to set levels of harvest.

In some jurisdictions, specified disturbance types require immediate stoppage of operations and amelioration, or require rehabilitation after harvesting. In Eastern Canada, where water quality for fisheries is a major concern, specified rut depths and lengths are not permitted, regardless of an apparent low risk for sediment delivery to streams (Lock 2001).

Recommendations: Principal requirements of soil disturbance surveys should be specified after review of existing systems and the literature.

A critical review of methods for assessing or monitoring soil disturbance is needed. This would identify advantages and disadvantages of various methods, and facilitate integration of ideas into several alternatives to fit specified objectives, sampling accuracy, and risk tolerance. The desired outcome should be consensus on a visual

classification system (element one) and several optional methods for monitoring disturbance (element two) without attempting to identify a best method.

A reliable soil-disturbance survey or monitoring system should address the following sampling considerations:

- The sampling method should provide even-coverage over the entire area being monitored. Low-intensity, random sampling (e.g., cluster sampling) seldom provides this but it can be achieved by applying surveys to smaller strata determined through more cursory walk through assessments of an overall operating area.
- The system should be cost-effective and provide meaningful data.
- Whenever possible, the system should use the binomial distribution (e.g., data point observations considered independent and summarized in terms of presence or absence of "counted" disturbance); this typically affords narrower confidence intervals at lower cost.
- The total (base) area to which disturbance limits (standards) apply needs to be specified when reporting percentages of disturbed soils. Permanent-access disturbance (roads) represents a loss from the timber-harvesting landbase and is often calculated as a percentage of that landbase (gross area). In contrast, on-block disturbance is often calculated as a percentage of what is referred to in B.C. as the net area to be reforested. It is important to make these distinctions to avoid confusion.
- Harvesting and monitoring costs could be reduced if some disturbance types proved inconsequential to productivity or if some soil types are proven to be more resilient to disturbance. Clearly, more research is needed to provide estimates of productivity changes on common disturbance types.

Develop reliable methods to rate soils for their relative vulnerability to compaction, rutting, displacement, and erosion.

Problem statement

Various methods exist for rating soils for their vulnerability (resiliency) to specified disturbance processes. Each method was developed for a specific geographic area. Some criteria or factors used to rate soil risk in the Northwest will differ greatly from those used in southern U.S.A., but the principles and main factors used for rating soils should be similar. We need to evaluate the merits of alternative methods across geographic areas and identify comparable risk-classes that are (1) useful for soil disturbance guidelines and (2) validated by operational and research results. Comparability facilitates interpretation and application of research results, and sharing operational experiences, guidelines, and protocols across geographic areas.

Background

Risk-rating methods focus on the relative, inherent hazard (risk) of a given soil to soil-degrading processes. Risk ratings are interpretations or predictions of soil vulnerability to a specified process (compaction, rutting, displacement) when a specified activity is performed under specified conditions. Soil risk-ratings are normally based on descriptive information for each mapping unit identified in detailed soil surveys. By various means, soil mapping units are rated for their susceptibility to a degrading process. In the absence of detailed soil classification and mapping, however, indirect interpretations are made based on site-specific data. Five soil-disturbance hazards for the Forest Practices Code Act of B.C. (B.C. Ministries of Forest and Environment 1995b)

were originally defined and are still used in harvest planning and operational monitoring: soil compaction, displacement, forest floor displacement, surface soil erosion, and mass wasting. Wherever risk ratings are based on soil maps, actual soil conditions must be verified on the site.

Soil risk-ratings can assist planning of forest operations. The operational challenge is to minimize the area of detrimental disturbance. To meet this challenge, we need to consider both inherent site factors and manageable factors that can mitigate disturbance. Manageable factors include timing of harvest, avoiding wet soils, designating equipment and harvesting layout.

A research challenge is to validate risk ratings or predictions of soil response and, more importantly, to quantify the linkage between change in soil properties and consequences for tree growth, erosion, and hydrologic processes. For example, does compaction always reduce tree growth or increase erosion?

Because compaction, puddling, and displacement are of particular concern in the Pacific Northwest, each will be discussed in detail as to (1) their effects on soil properties and processes, (2) factors used to predict soil risk, and (3) reported consequences for tree growth.

Soil Compaction and Puddling

Risk-rating systems to minimize compaction focus on soil physical properties (e.g., texture, coarse fragments, organic layers), often combined with site factors such as drainage or moisture regimes.

Soil risk factors

The B.C. Ministry of Forests' compaction-hazard key is an example of a simple key based mainly on soil texture and coarse fragment content (Table 3). Because wet soil conditions occur on all sites in some period each year, and most soils in B.C. have dense subsoils close to the surface, the B.C. key does not consider moisture status of the site or depth of surface soil (depth to dense subsoil) as discriminating factors. This approach may be too simple for other regions where soils remain moist much of the year or where no winter season enables low-impact harvest. In application, hazard ratings need to be tempered with seasonal climatic conditions.

Textural classes, as defined by the Canadian System of Soil Classification (Day 1983) or the USDA-NRCS, are weak indicators of soil resilience to mechanical stress. Problems include: (1) in textural analysis, it is not uncommon that some of the soil minerals influencing in-situ behavior are removed from the sample before texture determination (e.g. organic matter, calcareous material, iron and aluminum oxides); (2) some texture classes have a very large range in clay content (e.g. 0 to 28% for silt loam); and (3) some clay minerals respond differently to mechanical forces, exhibiting different cohesive properties like plasticity and stickiness. Therefore, to predict soil behavior, we need to supplement soil textural classes as a factor used in soil risk ratings.

Soil consistence as defined in the Canadian System of Soil Classification (Day, 1983) has provided for useful interpretations for soil tests for harvesting trafficability (Curran 1999; Curran et al. 2000a). Moreover, a test group of college students more accurately and precisely determined moist consistence (plasticity) than textural classes. As expected, "plastic" soils varied in actual clay content, presumably because their clay minerals differ. Content of sand and silt also affected plasticity. Siltier soils were plastic at clay contents as low as 12% (Curran, unpublished data). Although use of soil consistence classes did not change soil compaction ratings, it alerts users to soil

conditions that are more likely to lead to compaction and rutting. Similar interpretations could be made for erosion and mass wasting. Figure 3 demonstrates how plasticity relates to the texture triangle (note that silt loam encompasses three plasticity classes).

Tree performance and compaction

Soil compaction and puddling are of particular concern in timber-harvesting operations because of their immediate effects on soil properties and roots of residual trees, and subsequent effects on regeneration. Compacted soils may impede root growth because compacted and puddled soils have greater penetration resistance, lower aeration porosity, and slower rates of infiltration and hydraulic conductivity. Aeration porosity is a reliable indicator of how compacted a soil has become. Lowered aeration porosity reduces gas exchange that affects oxygen and carbon dioxide concentrations in the soil; this may reduce physiologic functions of roots and lead to root mortality during wet conditions. Compacted soils remain wet longer, further affecting seedlings due to lower soil temperature and poorer aeration.

In some coarse-textured soils, compaction may increase water-holding capacity and increase tree growth (Powers and Fiddler 1997; Stone et al. 1999). Coarse-textured soils typically have lower compaction-hazard ratings. Tree growth on rehabilitated landings (Bulmer and Curran 1999; Plotnikoff et al. 1999) and haul-roads (Curran, unpublished) demonstrate that sandier soils appear repairable following compaction.

However, texture classes may be too broad to be a predictor of impacts on tree performance after disturbance. In a 15-year-old stumping trial in southern B.C., Wass and Senyk (1999) found that tree growth was reduced on a soil with 12 % clay (Gates Creek soil), but not increased significantly on soil with 4 % clay. Yet, both soils were classified as gravelly sandy loam texture.

A further example of the variable nature of tree growth after soil disturbance was reported for aspen regeneration and growth in the Lake States (Stone 2001). Much lower density of suckers was measured on heavily disturbed (rutted) soil, and a highly significant negative relation existed between first-year height growth and an area-weighted index of soil disturbance (Stone and Elioff 2000). The site with the greatest reduction in aspen sucker density, however, was compacted during the spring when suckers were emerging. Thus, timing of the operations confounded response across sites. In other situations, differences among reported growth response can be explained by differing soil sensitivity to compaction or severity and extent of compaction among study sites or replicates within a site. Valid inferences about cause and effect require reliable data and careful consideration of treatments and site condition.

Slower rates of moisture infiltration and hydraulic conductivity in compacted or puddled soil can increase runoff during rainfall and snowmelt. Increased runoff from a cutblock can affect downslope sites, natural drainage features, and other resource values due to erosion and sedimentation. Increased runoff also means less water is stored on-site for tree growth during summer drought. These hydrologic effects are consequences of concentrated disturbance like main skid trails; however, effects of more dispersed traffic are difficult to study and clear relationships have not been elucidated to our knowledge (D. Toews, Research Hydrologist, BCMOF, Nelson, personal communication, 1999).

Forest Floor Displacement

Soil risk factors

Forest floor displacement is likely of greatest concern in northern temperate forests because much of the organic matter and nitrogen capital exists in the forest floor. In northern forests of the B.C. Interior, it is not uncommon for the forest floor to contain

over 50% of the total soil nitrogen and 80 % of the phosphorus. Conservation of the forest floor is important because many B.C. forest sites are nitrogen deficient. Curran et al. (1990) presented a scheme for rating hazard of forest floor displacement when planning site preparation in B.C that is still recommended (Curran et al. 2000a).

Tree performance

We need to better understand the effects of organic matter removals, the role of coarse woody debris, and the impacts of site preparation (tillage and/or vegetation control) on long-term site productivity (Stone et al. 1999; Fleming et al. 200x). Stone et al. (1999) reported that increasing intensity of organic matter removal decreased both diameter and height growth of aspen on sandy soils in the Lake States region of the U.S.A. Remedial tillage also affects physical properties and surface organic matter content. Root-raking in B.C. reduced tree growth on soils that were root-raked, but it is not clear if this is due to effects of tillage on soil structure, actual soil particles (e.g., tephra from volcanic ash deposition), and / or on organic matter manipulation. Further study is warranted if widespread tillage of similar soils were being considered.

Soil Displacement

Soil displacement is the lateral movement of mineral soil by moving equipment and logs. Displacement includes excavation, scalping, exposure of underlying materials, and burial of more fertile surface soils. Three effects of displacement can compromise soil productivity and site hydrology: (1) exposure of unfavorable subsoils (dense, gravelly, or calcareous with high pH); (2) redistribution and loss of nutrients; and (3) alteration of slope hydrology, which can lead to the hydrologic effects discussed previously with compaction. In addition, exposure of mineral soil can lead to erosion on steep slopes and

certain soil textures; this is the subject of watershed analyses and erosion ratings that are not discussed here.

Soil risk factors

Topsoil depth is the key indicator of soil-displacement risk. In northern temperate forests, soils on glaciated terrain are often shallow. Many nutrients are biocycled and concentrated in the forest floor and the top 20-cm of mineral soil, especially in cooler climates. Therefore, we need to avoid displacing fertile topsoil too far from seedlings, and to maintain the volume of topsoil available for rooting. The presence of unfavourable subsoils or water tables also warrants a high risk rating. Under other climatic conditions and with older soils, soil displacement is of more or less concern, depending on total soil depth and, in very old soils, on the extent of leaching and natural acidification.

Tree performance

Displacement of topsoil has reduced tree growth when high pH subsoil are exposed (Smith and Wass 1979), and when rooting volume is largely restricted to subsoils of poor fertility or limited moisture-holding capacity (Clayton et al. 1987).

Recommendations. Existing methods for risk-rating soils should be reviewed, and reliable methods and criteria identified.

Although soils can be mapped at a variety of scales and with a variety of objectives, we encourage detailed soil mapping (1:24,000 scale or larger) and representative descriptive data for each mapping unit. Soils mapped in the U.S.A. as part of the NASIS are mapped at the land type or land type- phase level of a hierarchy of ecological units;

map scale is usually 1:24,000. This is the level at which most direct risk-rating methods have been developed. One still needs on-site inspection to confirm accuracy of the mapping and hence the actual soil series present (to be rated). In the absence of detailed soil mapping, each area proposed for harvest requires its own soil assessment as part of harvest planning; this is the procedure used in B.C. (Curran et al. 2000a).

Other bases for soil risk rating should be considered. Burger and Kelting (1998), for example, noted a clear relationship between Least-Limiting Water Range (LLWR) and productivity on various disturbance types. This characteristic should be evaluated for a range of soils. Further research is warranted on both LLWR and soil plasticity.

We currently have methods for risk-rating soils. We should now test their validity by measuring the effects of operational practices on soil characteristics and, ultimately, on tree growth. Results of this validation monitoring may warrant changes in rating systems and guidelines.

Conservation of litter layers and topsoil probably is important in all forested ecosystems, particularly those on soils with a low silt and clay content (Stone et al. 1999). Reported effects of disturbance on organic matter and organic matter dynamics need to be compared and synthesized. Additional studies across a wider range of sites are needed to understand consequences of both forest floor and soil displacement and of soil compaction on soil processes and tree growth. The decade-old Long-term Soil Productivity Study in the U.S.A. and Canada is designed to meet these needs; this continuing effort should be supported.

Summary and final recommendations

We discussed and recommended development of more uniform and effective: (1) soil disturbance categories; (2) monitoring protocols that facilitate comparison and

transportability of operational and research results within and across geographic regions and jurisdictions; (3) ratings of soils for risk of compaction, rutting, and displacement.

To support this initiative, a wealth of completed and current work needs synthesis. Products and deliverables that should be considered by include:

- State-of-the-art reviews and position papers about soil disturbance categories, alternative monitoring methods, and risk-rating systems.
- Recommended definitions of potentially detrimental soil disturbance types for specified areas.
- Coordinated training and extension materials for forest workers and lay persons.
- Effective methods for converting operational and research information into periodically updated soil management guidelines and BMPs.
- Common soil disturbance guidelines for similar soils.
- Continued involvement with eco-certification and sustainability protocols to ensure their operational relevance.

These products will not only facilitate collection of more comparable data by states, provinces, USFS regions, and private ownerships, but also ensure a more seamless process for reporting at national and international levels where appropriate. Additionally, these products will improve operational relevance of research results.

Organizations and jurisdictions need to consider how their science and technology programs can contribute to achieving our objective of a common approach to soil disturbance. We suggest that regional working committees complete these products. For example, some regional issues could be addressed by the newly created "Soil Disturbance Working Group" of the Northwest Forest Soils Council, or by a currently proposed "National Working Group on Forest Soil Disturbance" in Canada. Internationally, umbrella organizations such as the International Union of Forest Research Organizations

(IUFRO), the International Energy Agency (IEA), or the organizers of North American Forest Soils Conferences could provide leadership in this area. Although it is more realistic to start regionally (such as in the Pacific Northwest), potential cooperators at all levels should be engaged early to ensure general acceptance of a common language and congruent approaches.

Timing is critical to meet a pressing need for new monitoring as required by international protocols. Given adequate support by sponsoring jurisdictions, initial products (e.g., disturbance types, risk-rating systems, and monitoring methods) for reporting research and monitoring results could be drafted in a relatively short period of time. Other products (e.g., an adaptive soil management process, operational reporting to satisfy certification requirements, or comparison of guidelines) would take longer. Final adoption of recommendations, however, is an administrative issue and beyond the scope of technical committees. The authors plan to pursue these Elements in the Pacific Northwest and encourage similar efforts in other regions and at the national and international levels.

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1 Table 1. Interim severity classes for soil disturbance in the Wallowa-Whitman National

2 Forest (Modified from USFS 2001)

Class 0: Undisturbed Natural State **Soil surface:** • No evidence of past equipment operation. • No depressions or wheel tracks evident. • Litter and duff layers present and intact. • No soil displacement evident.	**Class 1: Low Soil Disturbance** **Soil surface:** • Faint wheel tracks or slight depressions evident and are <6 inches deep. • Litter and duff layers present and intact. • Surface soil has not been displaced and shows minimal mixing with subsoil. **Soil resistance to penetration with tile spade or probe:** • Resistance of surface soils may be slightly greater than observed under natural conditions. Concentrated in top 0-4 inch depth. **Observations of soil physical conditions:** • Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 0-4 inches.
Class 2: Moderate Disturbance **Soil surface:** • Wheel tracks or depressions are >6 inches deep • Litter and duff layers partially intact or missing. • Surface soil partially intact and may be mixed with subsoil. **Soil resistance to penetration with tile spade or probe:** • Increased resistance is present throughout top 4-12 inches of soil. **Observations of soil physical conditions:** • Change in soil structure from crumb or granular structure to massive or platy structure, restricted to the surface 4-12 inches. • Platy structure is generally continuous. • Large roots may penetrate the platy structure, but fine and medium roots may not.	**Class 3: High Disturbance** **Soil surface:** • Wheel tracks or depressions highly evident with depth being >12 inches deep. • Litter and duff layers are missing. • Evidence of topsoil removal, gouging and piling. • Soil displacement has removed the *majority* of the surface soil. Surface soil may be mixed with subsoil. Subsoil partially or totally exposed. **Soil resistance to penetration with tile spade or probe:** • Increased resistance is deep into the soil profile (>12 inches). **Observations of soil physical conditions:** • Change in soil structure from granular structure to massive or platy structure extends beyond the top 12 inches of soil. • Platy structure is continuous. • Roots do not penetrate the platy structure.

Table 2. Soil disturbance definitions from the B.C. Forest Practice Code Act, Operational Planning Regulations* (abbreviated for this paper with clarification provided in [square brackets]).

Compacted area - an area of soil that [requires rehabilitation]

(a) is greater than 100 m^2 in area and greater than 5 m wide,

(b) has a moderate, high or very high soil compaction hazard or the assessment of its soil compaction hazard was not done [such as cable-harvested areas]

(c) has been compacted by equipment travelling over it, and (d) has one or more of the following attributes:

(i) altered soil structure or increased density relative to the surrounding undisturbed soil; (ii) soil puddling; (iii) compacted deposits of forest floor, fine slash / woody debris overlaying or crushed into the mineral soil;

Dispersed disturbance - areas of soil occupied by dispersed trails, gouges and scalps;

Excavated or bladed trail - constructed trail that has [requires rehabilitation]

(a) an excavated or bladed width greater than 1.5 m, and (b) mineral soil cutbank height greater than 30 cm;

Dispersed trail - an area that is not a compacted area but that, due to equipment traffic on the soil, has the following attributes: (a) impressions or ruts in the soil that are at least

(i) 30 cm wide, 2 m long and a minimum of 15 cm deep where depth is measured from the surface of the undisturbed forest floor to the deepest point in the cross-section over the entire length of 2 m, or

(ii) if the area has a high or very high soil compaction hazard, 30 cm wide, 2 m long and a minimum of 5 cm deep where depth is measured from the surface of the undisturbed mineral soil to the deepest point in the cross-section over the entire length of 2 m;

(b) has the same attributes as Compacted Area (d) on an area of soil at least 1 m x 2 m that has a moderate, high or very high soil compaction hazard

Gouge - an excavation into the mineral soil that is: (a) deeper than 30 cm, (b) deeper than 5 cm where it covers: (i) at least 80% of a 1.8 m x 1.8 m area, or (ii) an area of at least 1 m x 3 m, or (c) to the depth of the underlying bedrock;

Scalp - an area in which the forest floor has been removed from: (a) over 80% of a 3 m x 3 m area or

(b) over 80% of a 1.8 m x 1.8 m area if the area: "....(ii) has a very high soil displacement hazard,

(iii) has a very high soil compaction hazard or soil erosion hazard,"

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*The general BCMOF web site where these and other FPC information can be located is: http://www.for.gov.bc.ca/tasb/legsreg/fpc/fpc.htm

Table 3. Hazard Key for Soil Compaction and Puddling (B.C. Ministries of Forests and Environment 1995b).

SOIL TEXTURE[a] (0-30 cm)		**HAZARD RATING[b]** *moisture regime*	
		Xeric-subhygric[c] (H horizons <20 cm)	***Subhygric-subhydric***[d] (H horizons ≥20 cm)
Fragmental Coarse fragments >70%		**L**	**M**
< 70 % Coarse Frements	Sandy S, LS	**L**	**VH**[e]
	Sandy Loam SL, fSL	**M**	
	Silty/Loamy SiL, Si, L	**H**	
	Clayey SCL, CL, SiCL, SC, SiC, C	**VH**	

[a] Use dominant soil texture and coarse fragment content of the upper 30 cm of mineral soil to assess compaction hazard. If a pronounced textural change occurs within the upper 30 cm (e.g., silty over sandy soil), then use the more limiting soil texture, providing it amounts to 5 cm of the top 30 cm.

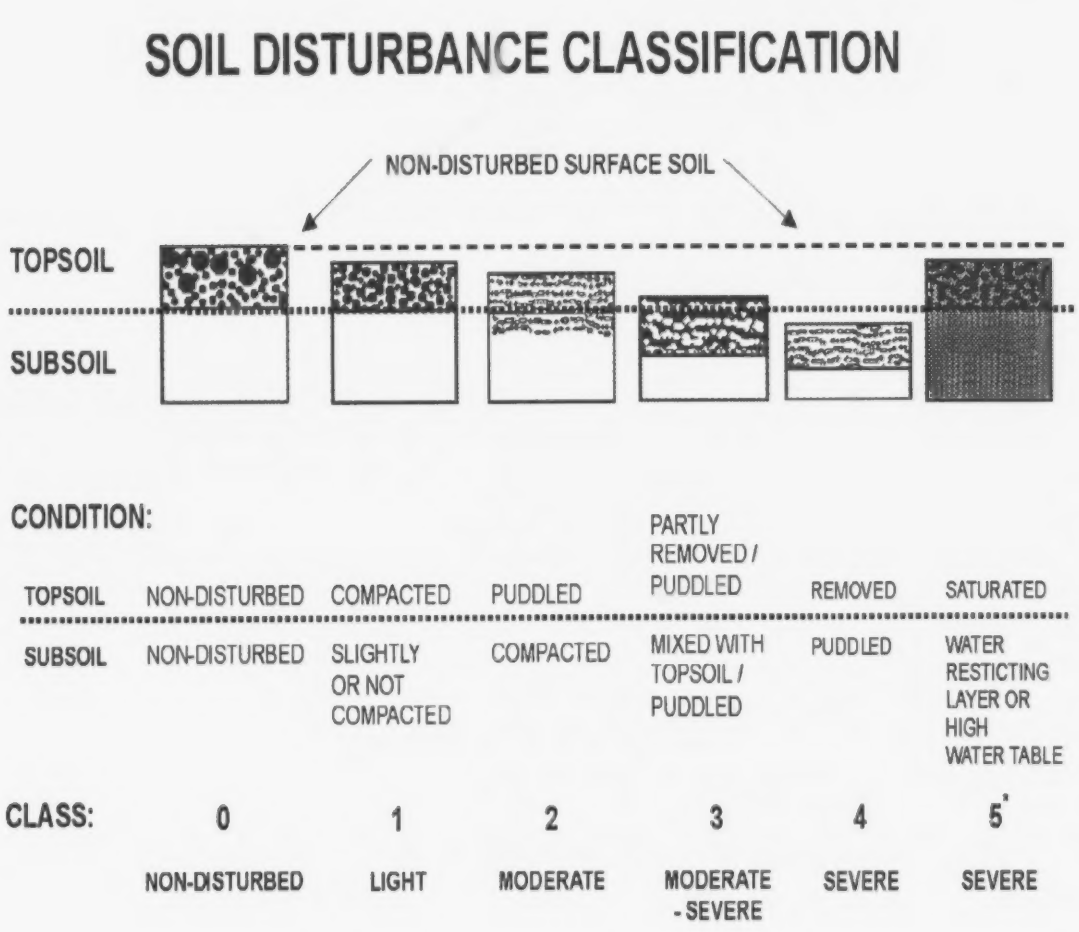
[b] L=Low; M=Moderate; H=High; VH=Very High.

[c] Use this column for subhygric sites with forest floor H-horizons <20 cm thick.

[d] Use this column for subhygric sites with forest floor H-horizons ≥ 20 cm thick.

[e] ORGANIC SOILS composed of more than 40 cm of wet organic material or forest floors >40 cm (including Folisols < 40 cm) are susceptible to rutting due to their very low load- bearing strength materials. Consequently, these organic materials have a high soil displacement hazard and a very high soil compaction and puddling hazard.

Figure 1. Soil disturbance categories used by the Weyerhaeuser Company in western Washington and Oregon (Scott 2000)


SOIL DISTURBANCE CLASSIFICATION
NON-DISTURBED SURFACE SOIL
TOPSOIL
SUBSOIL
CONDITION:
TOPSOIL NON-DISTURBED COMPACTED PUDDLED PARTLY REMOVED / PUDDLED REMOVED SATURATED
SUBSOIL NON-DISTURBED SLIGHTLY OR NOT COMPACTED COMPACTED MIXED WITH TOPSOIL / PUDDLED PUDDLED WATER RESTICTING LAYER OR HIGH WATER TABLE
CLASS: 0 1 2 3 4 5*
NON-DISTURBED LIGHT MODERATE MODERATE - SEVERE SEVERE SEVERE
*CLASS 5 SATURATION APPLIES TO ANY DISTURBANCE THAT CAUSES THE SOIL TO BE SATURATED FOR TEN (10) OR MORE DAYS.

1

Always Counted
Deep Gouge
Wide Gouge
(80% of 1.8 m x 1.8 m)
Long Gouge
(100% of 1.0 m x 3.0 m)
Very Wide Scalp*
(80% of 3.0 m x 3.0 m)
* Scalp means the forest floor has been removed.
Wide Scalp*
(80% of 1.8 m x 1.8 m)
Counted when: VH soil displacement, compaction or erosion; or moderate or high likelihood of landslides; or the soil hazards have not been documented in an operational plan.
Forest Practices Branch
B.C. Ministry of Forests
Soil Disturbance Card
Wheel/Track Rut
Counted on: All Sites
Wheel/Track Rut
Counted on: Very High and High Compaction Hazard Sites
or where soil hazards have not been documented in an operational plan.
Repeated Machine Traffic
Counted on: Very High, High and Moderate Compaction Hazard Sites
or where soil hazards have not been documented in an operational plan.
Compacted Areas*: counted on same sites as "repeated machine traffic," illustrated above, but compacted areas are larger (i.e., must be >100 m² and > 5 m wide).
Corduroyed Trail*: logs and woody debris placed side-by-side to form a surface > 2 m long capable of supporting machine traffic.
*Must be rehabilitated unless exempted by district manager
**Must be preapproved and may require rehabilitation.
Temporary Excavated/BladedTrails**
Unfavorable Fill Slope Material (won't support tree growth)
Favorable Fill Slope Material

2

3

4 Figure 2. Field card showing disturbance types counted under B.C. Forest Practices

5 Code.

6

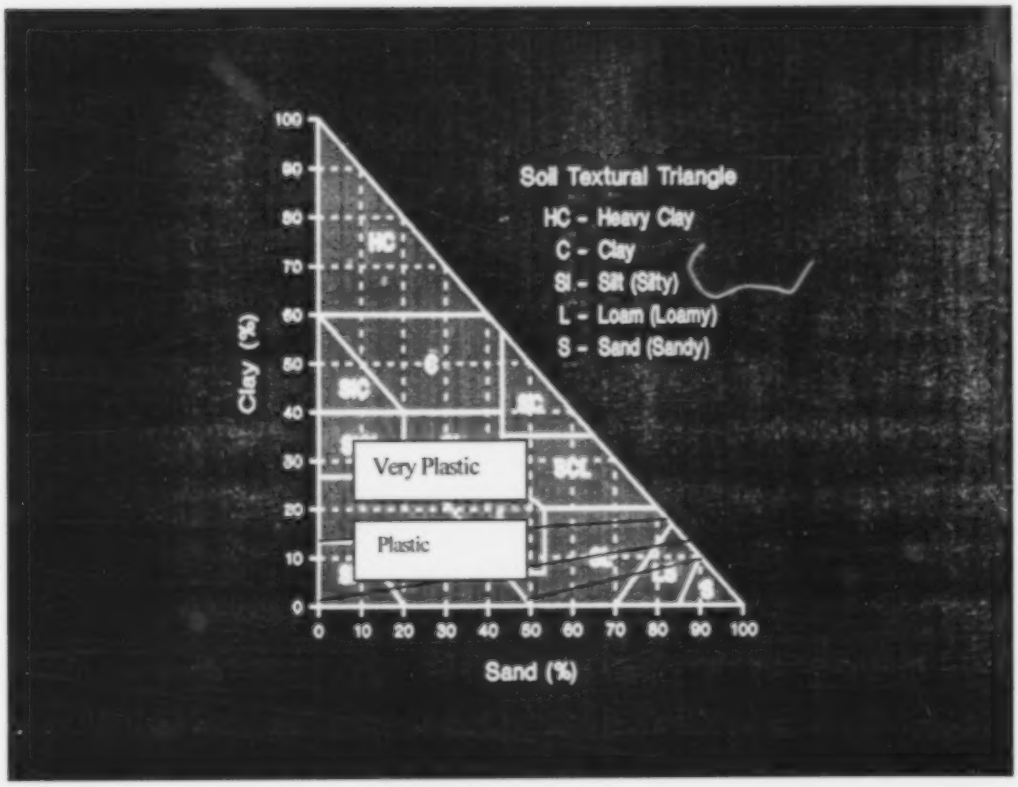
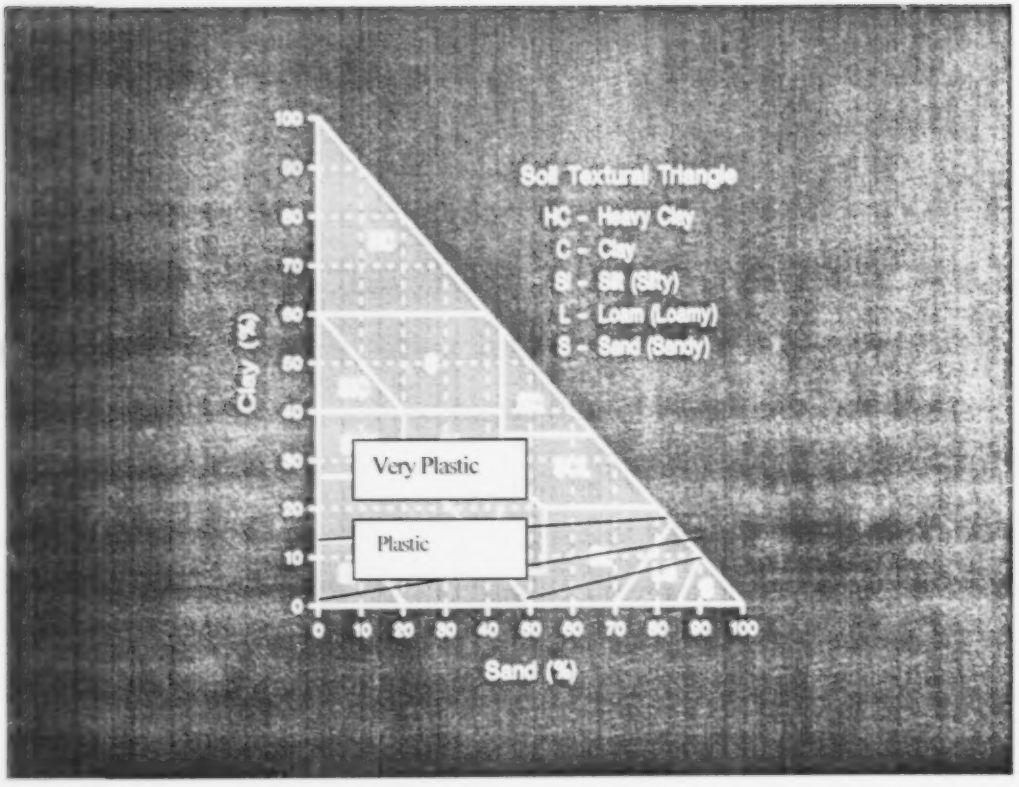


Figure 3. Demonstration of how soil consistence (plasticity) categories fall into the soil texture triangle, based on 48 samples of varying clay and sand content. The three black lines delineate, from the bottom right corner: non-plastic, slightly-plastic, plastic, and very plastic, respectively (Curran, unpublished data).



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